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Analyzing the relationship between urbanization, food supply and demand, and irrigation requirements in Jordan

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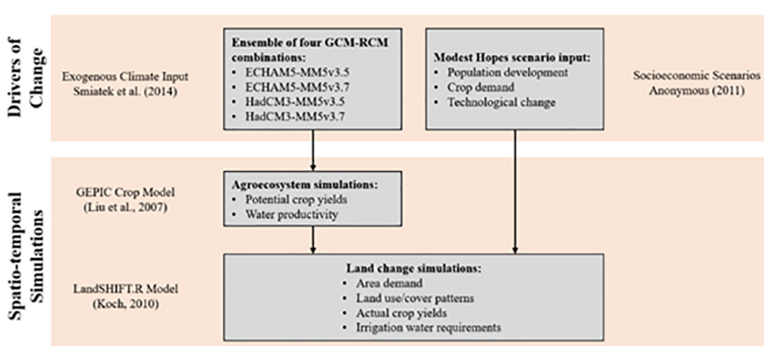
HIGHLIGHTS

- We used simulation models to assess urbanization effects on land/water resources in Jordan.
- Productive farmland is available to buffer the effect of urban expansion farmland displacement.
- Climate change and increase in food demand lead to steep increases in cropland area and irrigation water requirements.
- Investments and action are required to prepare for future irrigation water needs.

GRAPHICAL ABSTRACT



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ABSTRACT

The landscape surrounding urban areas is often used as farmland. With the observed expansion of urban areas over the last decades and a projected continuation of this trend, our objective was to analyze how urbanization affects food supply and demand in The Hashemite Kingdom of Jordan. We used a chain of simulation models covering components of the atmosphere (climate simulations), biosphere (crop yield calculations), and anthroposphere (simulations of urban expansion and land-use change) to calculate the effect of farmland displacement on land and water resources (hydrosphere). Our simulations show that the displacement of farmland itself has hardly any effect on cropland demand, crop yields, or irrigation water requirements. These results indicate that Jordan has sufficient productive areas available to buffer effects of urban expansion on food production for the next decades. However, this picture changes dramatically once we include changes in socioeconomy and climate in our simulations. The isolated effect of climate change results in an expected increase in irrigation water requirements of 19 MCM by 2025 and 64 MCM by 2050. It furthermore leads to an increase in cropland area of 147 km^2 by 2025 and 265 km^2 by 2050. While the combined analysis of urban expansion, climate change, and socioeconomic change makes optimistic assumptions on the increase in crop yields by 2050, the results still indicate a pronounced effect on cropland demands (2700 km^2) and a steep increase in irrigation water requirements (439 MCM). Our simulation results highlight the importance of high resolution, spatially explicit projections of future land changes as well as the importance of spatiotemporal scenario studies at the regional level to help improving water planning strategies.

1. Introduction

Worldwide, the percentage of urban population has grown from 30% in 1950 to 54% in 2014 (United Nations and Department of Economic

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and Social Affairs (Population Division), 2015a), which resulted in an increase in urban areas even exceeding population growth rates (Seto et al., 2011). Projections indicate that this trend is expected to persist (Seto et al., 2012), and even accelerate in some regions of the world, e.g., the Middle East (United Nations and Department of Economic and Social Affairs (Population Division), 2015b). These urbanization trends are likely to have a considerable effect on biodiversity (Seto et al., 2012), water quality, and urban microclimate (Foley et al., 2005). Another important consequence of urban expansion is the loss, displacement, and degradation of fertile farmland - often located in proximity to urban areas - with significant implications for food security (Shi et al., 2016). While most studies that analyze the relationship between urbanization and food production focus on food supply (i.e., implications on farmland) (López et al., 2001; Pandey and Seto, 2015; van Vliet et al., 2017), Seto and Ramankutty (2016) emphasize the importance of food demand as an essential component of the food production system.

The Hashemite Kingdom of Jordan is one example of a country that is likely to experience the detrimental effects of urbanization on farmland. Over the last decades, Jordan has seen considerable population growth, and more than 80% of Jordan's population lives in urban areas. Most large cities are located in the north-western part of the country - a fertile area (part of the "Fertile Crescent") that receives the highest mean annual precipitation in Jordan. The north-western part is also where a large percentage of the farmland is located, with more than 90% of farmland within a 50 km radius of Jordan's three most populated cities. Besides the potential issues due to urbanization, Jordan's food production system is also likely to be negatively impacted by climate change, driven by increasing temperatures and decreasing precipitation (Smiatek et al., 2011).

Spatially explicit urban simulation models employing a Cellular Automata (CA) approach have been used for several decades to analyze urban expansion and changes in shape, structure, and composition of urban areas. Examples include the work of White and Engelen (1993), the SLEUTH model (Clarke et al., 1997), and the pattern-based FUTURES model (Dorning et al., 2015; Meentemeyer et al., 2013). Land change models, such as the widely used CLUE-S model (Verburg et al., 2002) and the regional to global scale LandSHIFT model (Alcamo et al., 2011; Schaldach et al., 2011), also use a CA approach. As compared to urban simulation models, these models emphasize the landscape as a whole and are better suited to analyze the spatial and temporal relationships between different land uses, e.g., the competition for land resources between urban land use and land use for production of agricultural commodities. One feature of the land change model LandSHIFT is the use of demand for agricultural commodities and not area demand to drive changes in land use and land cover (Schaldach et al., 2011; Schaldach and Koch, 2009). This is realized through a soft coupling of LandSHIFT to crop productivity models such as LPJmL (Bondeau et al., 2007) or GEPIC (Liu et al., 2007), which provide crop productivity simulations for specific biophysical conditions (e.g., climate or soil) and crop management (e.g., fertilizer input or irrigation levels). This endogenous representation of crop productivity and water productivity allows for the inclusion of different food production intensities and the inclusion of effects of climate change on food production and natural resources (farmland area, crop yields, and irrigation water requirements) (Schaldach et al., 2012).

To better understand the intricate relationships among different components of the food production system - namely food supply (influenced by climate change and urban expansion) and food demand (driven by population growth and dietary changes) - we used a sequence of simulation models producing downscaled climate projections, calculations of crop productivity, and spatially explicit scenarios of land use and land cover change. We applied this chain of simulation models and their output data to investigate the relationship between urbanization, food production, and their combined effects on land and water resources. In our analysis, we include potential changes in food supply due to the expansion of urban areas and resulting displacement of farmland under climate change conditions. We furthermore include potential changes in food demand caused by population growth, changes in technology, and changes in dietary composition. Changes in dietary composition are represented through underlying assumptions on increases in per capita availability of calories from all foods and a trend towards a more meat-based diet as described by the Global Environmental Outlook 4 (GEO4). We used LandSHIFT.R, which has been developed and extensively tested for the Middle East's biophysical conditions (Koch, 2010; Koch et al., 2008, 2012a). We apply the model to investigate how potential future changes in food supply (driven by urban expansion and climate change) and food demand (driven by population growth and dietary changes) may affect the food production system (focusing on location, productivity, and irrigation requirements) in a region suffering from severe water scarcity.

2. Materials & methods

2.1. Study area

We conducted the study for the Hashemite Kingdom of Jordan, which covers a total area of 89458 km^2 (Fig. 1). Over the last decades, Jordan has experienced considerable growth, with population numbers increasing from 2.181 million in 1980 to over 4.797 million in 2000 and 6.607 million in 2014 (The World Bank Database). About 83% of the population lives in urban areas (United Nations and Department of Economic and Social Affairs (Population Division), 2015a), and the population of the six largest cities adds up to about 45% of Jordan's total population (Amman - 1.276 million, Zarqa - 0.793 million, Irbid - 0.306 million, Russeifa - 0.268 million, Wadi as Sir - 0.181 million, and 'Ajlun - 0.126 million). All six of Jordan's largest cities are located in the north-western part, which makes this area the most significant domestic market for agricultural products.

The north-western part of the country also receives the highest amount of mean annual precipitation and, hence, the majority of Jordan's farmland is located in this region. According to MODIS data, in 2001 96% of Jordan's cropland was located within 50 km of Amman, Zarqa, or Irbid. Jordan's actual amount of renewable freshwater is 161 m^3 per capita and year (Food and Agriculture Organization of the United Nations (FAO), 2016). This value is well below the threshold for chronic water scarcity defined as 1000 m^3 per capita and year (Falkenmark and Rockström, 2004). With about 65%, agricultural activities use a significant part of the available freshwater resources according to the FAOSTAT database, which indicates that urbanization may affect the location of farmland and the required water amount for agricultural activities.

2.2. Simulation workflow

One of the innovative features of this study is the evaluation of the isolated and combined effect of change in climate and extent of urban area on land and water resources. Unlike existing studies that focus on the displacement aspect of this relationship (e.g., van Vliet et al., 2017), the workflow of this study allows the analysis of displacement effects on crop yields and irrigation requirements. For this, we applied a two-step simulation approach (Fig. 2). The workflow of our simulations has the four major components climate projections, socioeconomic scenario data, GEPIC simulations, and as the final step, land change scenario simulations. We use an ensemble of climate projections for the calculation of potential crop yields and water productivity. We then use these simulations in combination with socioeconomic scenario input as drivers of change in land use and land cover, calculated with LandSHIFT.R.

2.3. Simulation experiments

Because the location of major cities coincides with fertile areas that receive high mean annual precipitation, we hypothesized that the

expansion of urban area leads to indirect land-use change in the form of displacement of farmland to other parts of the country, which is likely to have a considerable effect on both land and water resources. We expected the displacement to result in a decrease in average crop yields combined with an increase in area demand for crop production and an increase in irrigation water requirements. Based on this hypothesis, we formulated three research questions: (1) How do changes in food supply (climate change and the displacement of farmland due to urban expansion) affect land and water resources? (2) How do changes in food demand (population numbers, technological progress, and dietary composition) affect land and water resources? (3) How do the combined changes in food supply and demand affect land and water resources?

We developed a set of model runs that allow evaluating the isolated and combined effects of food supply and food demand on both land resources (area demand and crop productivity) and water resources (irrigation water requirements and water productivity). For those scenarios, we selected different drivers of change including Urban Expansion (UE), Climate Change (CC), and changes in SocioEconomic conditions (SE) as described below. We used all possible combinations of these three factors, resulting in three Food Supply scenarios (FS1 – FS3), one Food Demand scenario (FD1), and three combined scenarios (FSD1 – FSD3) (Table 1). We also calculated the baseline for which we did not include any of the factors and which does not include any change, but describes the conditions for the base year of the study (the year 2000).

We used the baseline simulation to compare it to the three FS scenarios to understand how changes in food supply affect land and water resources. We applied the FD scenario to address how changes in food demand affect land and water resources. The FSD scenarios are aimed at answering the third research question, i.e., how do the combined changes in food supply and demand affect land and water resources. Our analysis of the simulation results focused on four key components covering land and water resources: (1) area demand (urban, rainfed farmland, and irrigated farmland) and (2) crop productivity (average irrigated and rainfed crop yields), (3) irrigation water requirements and (4) water productivity.

2.4. Food supply

2.4.1. Urban expansion

The primary driver for urban expansion (UE) is growth in urban population. While population growth is typically tied to an increase in demands for agricultural commodities, we excluded these from the assumptions for UE to enable studying the isolated effect of expansion in urban areas on farmland displacement. For population growth, we used values from the "Scenarios of Regional Development under Global Change" that were specifically developed for the Jordan River region (Israel, Jordan, Palestinian Authority), through a multi-year scenario exercise involving a series of stakeholder workshops (Anonymous, 2011). This exercise includes four scenarios that differ regarding their assumptions on future economic development and shared use of transboundary water resources (Anonymous, 2011). We selected the "Modest Hopes" scenario (MH), which is characterized by economic growth and unilateral water division. Anonymous (2011) describes the situation under the MH scenario as

> "a future world in which outside donors invest heavily in the region to prevent deterioration of the political situation. The prosperity under this scenario leads to a politically stable situation in the region with limited informal cooperation (exchange of knowledge/technologies). The focus of water management is on increasing the supply of water by large scale desalination and waste water treatment and reuse, all on a high technical level."

Since our study tests several different factors (UE, CC, SE), we decided to use only one of the four scenarios for clarity. We specifically selected the MH scenario, because:

(1) With the recent approval of the Red Sea-Dead Sea canal project that includes large-scale desalination, the scenario covers significant developments in the region;
(2) Among the four scenarios, the MH scenario is one of the more moderate ones. However, it consistently provides the second highest assumptions regarding the primary drivers of change (e.g., population growth).

Hence, the MH scenario captures a good representation of the situation and recent developments in the study region while providing the opportunity to test the capacity of the land system under study. Fig. 3 shows the population numbers for MH, used for the scenarios FS1, FS3, FSD1, and FSD3.

2.4.2. Climate change

In our simulation experiment, climate data is necessary to elucidate the future state of food supply and water resources. We use climate projections as input for the calculation of potential crop yields, water productivity, and irrigation water requirements. These are determinants of area demand for domestic food production. To be able to provide a robust representation of climate inputs and understand the sensitivity of the simulation workflow to climate inputs, we used four different versions of climate projections for the Special Report on Emission Scenarios (SRES) A1B scenario (Nakicenovic and Swart, 2000). These climate inputs were provided by Smiatek et al. (2011), who calculated different projections for the Jordan River region with a spatial resolution of 18.6 km using a nested dynamic downscaling approach. They used output from the two Global Circulation Models ECHAM5 (fifth generation of the European Centre for Medium-Range Weather Forecast model (EC) with a parametrization package developed in Hamburg (HAM) at the Max Planck Institute for Meteorology (Roeckner et al., 2003, 2006)) and HadCM3 (U.K. Meteorological Office Hadley Centre Coupled Model, version 3 (Gordon et al., 2000)). They then used the GCM simulation results to drive two different model releases (version 3.5 (Chen and Dudhia, 2001) and version 3.7_4) of the MM5 Regional Climate Model (Dudhia, 1992). The climate simulations (ensemble mean) show a mean annual temperature increase of 2.1 K and a decrease in mean annual precipitation of 11.5% between the periods 1961–1990 and 2031–2060 (Smiatek et al., 2011). Furthermore, all climate simulations in this ensemble showed an increase in the heat wave duration index and the coefficient of variation values for annual precipitation (Smiatek et al., 2011).

With the projections based on the "representative concentration pathways" (Moss et al., 2010), more recent climate data is available. We decided to use the downscaled SRES A1B climate projections from Smiatek et al. (2011) in our simulation experiment for two reasons: First, few regional studies exist specifically for The Hashemite Kingdom of Jordan, evaluating the effect of climate on water resources. These studies typically use the SRES climate projections; examples include Al-Qinna et al. (2011), Smiatek et al. (2014), and Wade et al. (2010). Second, a study conducted by Smiatek and Kunstmann (2016)

Table 1
Description of scenario characteristics. "+" indicates factor considered in the scenario; "-" indicates factor not considered in the scenario.

Scenario name	Urban expansion	Climate change	SocioEconomic change
Baseline	−	−	−
FS1	+	−	−
FS2	−	+	−
FS3	+	+	−
FD1	−	−	+
FSD1	+	−	+
FSD2	−	+	+
FSD3	+	+	+

using five downscaled climate datasets showed that the new, downscaled climate projections for the Jordan River region based on the RCPs, are well within the range of simulations using the SRES scenarios. Hence, we decided to use the A1B climate projections that allow us to discuss and compare our simulation results in the context of other regional studies for Jordan.

2.4.3. Crop productivity and water productivity

We used high resolution, downscaled climate projections described above as input to GEPIC (Liu et al., 2007) – the GIS version of the crop and soil productivity simulation model EPIC (Sharpley and Williams, 1990). We used the four different GCM-RCM climate simulations for the periods 1971–2000 and 2035–2064 to calculate potential irrigated crop yields, potential rainfed crop yields, and crop water productivity/evapotranspiration for the two periods. These simulations form the basis for the projections of future farmland area and irrigation water requirements and allow us to answer questions regarding area demand and discuss the relationship between urbanization processes and farmland productivity. A detailed description of input data used to parameterize and run GEPIC for Jordan is provided in Koch et al. (2012a).

2.5. Food demand

2.5.1. Socioeconomic change

The socioeconomic (SE) change component in our analysis includes two factors: (1) increasing demand for agricultural products driven by population growth and changes in dietary composition, and (2) changes in crop yields (per hectare) due to advancements in plant breeding and agricultural management. The scenario assumptions regarding demand for agricultural products and dietary changes for the scenarios are based on calculations conducted for the United Nations Environment Programme Global Environmental Outlook 4 (GEO4). It is important to note that SE includes only the demand change, but not the population growth which is covered in the UE component. The separation was necessary to be able to study the isolated effects of urban expansion on farmland relocation. We use the values for projected demand increase and yield improvement specified for the MH scenario (Anonymous, 2011). Fig. 4 shows the corresponding values for the simulation period.

2.6. Land change simulations

For the last step in our simulation workflow (Fig. 2), we used a regional version of the global land change model LandSHIFT (Alcamo et al., 2011; Schaldach et al., 2011). We developed the regional version – LandSHIFT.R – specifically for the Jordan River region and tested it thoroughly (Koch et al., 2008, 2012a). LandSHIFT.R is a spatially distributed, dynamic simulation model that calculates alternative projections of potential changes in land use and land cover. The model uses a cellular automata approach to identify suitable locations for land change. Koch (2010) and Schaldach and Koch (2009) give a detailed description of the model functionality. We ran the simulation model for the territory of The Hashemite Kingdom of Jordan with a 30 arc sec spatial resolution, covering the period from 2000 until 2050 with a 5-year time step. Given the four different climate projections and eight different scenarios (Table 1), we ran 32 different simulations. The output for each of those simulations includes maps of land use/cover, average crop yields (rainfed and irrigated), and total irrigation water requirements in millions of cubic meters (MCM). LandSHIFT.R furthermore calculates a set of area statistics on the country level.

3. Results

3.1. Baseline simulation results

Fig. 1 displays the land use/cover map for the baseline (year 2000) and Table 2 shows the baseline areas for the focus land use categories of this study. Most of the rainfed and irrigated farmland is located in relative proximity to the urban centers and water sources (Jordan River and irrigation infrastructure such as the King Abdullah Canal (KAC)). Average crop yields – including the crop categories fruits, vegetables, and cereals – are 0.6 t/ha under rainfed conditions and 16.4 t/ha under irrigated conditions. The overall irrigation water requirements for crop production totals 321 MCM. Since we did not include any assumptions on the change in input data for this “scenario” the simulation results for the baseline do not change over the simulation period. In the following two sections, we compare the simulation results for the different scenario assumptions against the baseline conditions.

3.2. Food supply

3.2.1. The effect of urban expansion

The simulation results for the FS1 scenario show the effects of urban expansion. This scenario shows an increase in urban area of 370 km^2 by 2025 and 834 km^2 by 2050 (Tables 2, 3). Even though a moderate part of urbanization happens on former farmland, the displacement does not result in significant expansion of cropland (Fig. 5(a) and (d)). By 2025, the rainfed cropland increases by only 3 km^2 and irrigated cropland area show a decrease of 22 km^2. The results for the year 2050 are in the same order of magnitude. The simulations furthermore show a reduction of irrigation water requirements of one MCM by 2025 and 10 MCM by 2050 as compared to the baseline. Fig. 6 indicates that under the FS1 scenario, new farmland is allocated in the north-western tip of Jordan. The area along the Jordan River has comparably high mean annual precipitation values, which explains the reduction of irrigation water requirements as compared to the baseline.

3.2.2. The effect of climate change

The simulation results for the FS2 scenario display the effect of climate change. In contrast to the simulations without climate change, these results provide a range of results due to the four different input datasets for climate, crops yields, and water productivity. Hence, the values provided in Tables 2, 3 are ensemble means. Climate change has a pronounced impact on farmland area, crop yields, and irrigation water requirements (Fig. 5). Even though no demand increase is considered in this scenario, cropland area increases by 147 km^2 until 2025 and by 265 km^2 until 2050 (compared to the baseline). The area increase is solely driven by reduced crop yields due to changes in temperature and precipitation patterns (Fig. 5(b) and (e)). Fig. 5 also shows that climate projections introduce uncertainty the further into the future we project. The expansion of farmland caused by reduced crop yields is also tied to an increase in irrigation water requirements as displayed in Fig. 5 (c) and (f). The results show an increase of 19 MCM by 2025 and 64 MCM by 2050.

3.2.3. The combined effect of urban expansion and climate change

The simulation results for the FS3 scenario display the combined effect of urban expansion and climate change. Since they also include the climate-driven crop yield and water productivity calculations, these results also give a range of uncertainty introduced by the climate projection ensemble. The simulation results for the FS3 scenario are in the same order of magnitude as the results for FS2. Projections of urban expansion under FS3 are identical to the FS1 scenario. While there are minor differences between the FS2 and FS3 scenario in irrigated farmland area (1 km^2 for 2025), rainfed farmland area (2 km^2 in 2025 and 8 km^2 in 2050) and irrigation water requirements (1 MCM in 2025 and 2050), the difference does not exceed the range of model uncertainty. These results emphasize the marginal effect of farmland displacement due to urban expansion on farmland area demands and irrigation water requirements.

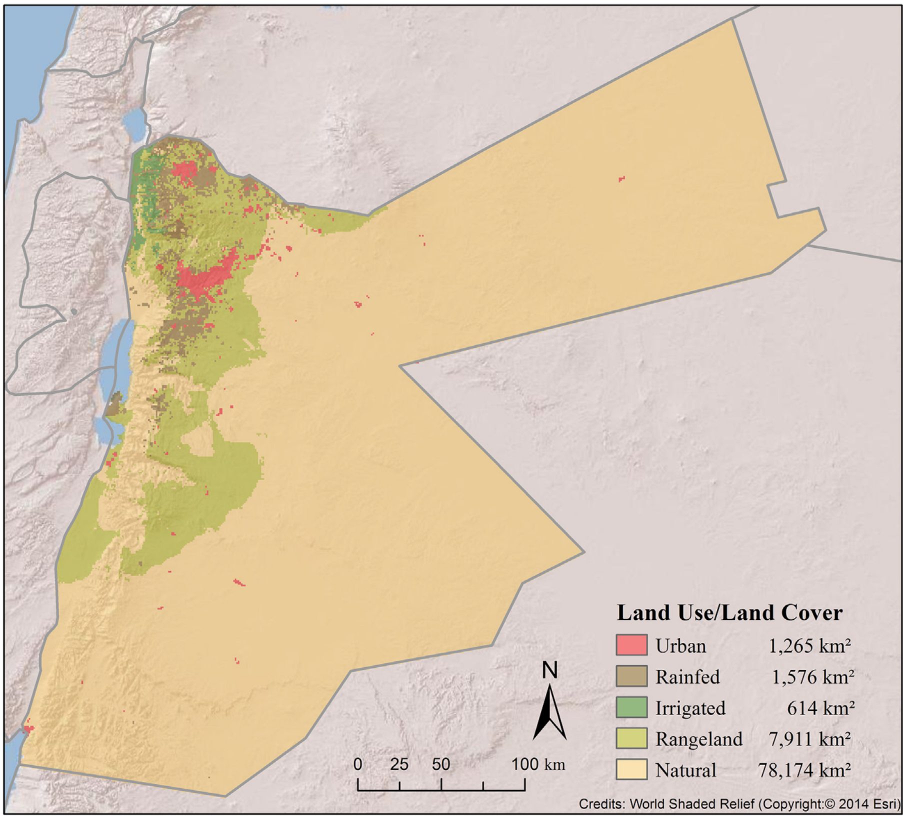

Fig. 1. In the study region, The Hashemite Kingdom of Jordan, the largest cities are located in the northwest of the country. These coincide with the areas of highest productivity, tied to high precipitation.

3.3. Food demand

The FD1 scenario explores the effect of socioeconomic change based on the assumptions regarding increasing crop demands and changes in dietary composition as described in Anonymous (2011). Because yield increase due to plant breeding and agricultural management advancements is part of the scenario assumptions, we see an increase in crop yields (mainly determined by irrigated crop yields) from 5.0 t/ha for the baseline to 6.7 t/ha by 2025 and 8.2 t/ha by 2050. Nevertheless, the simulation results for this scenario show by far higher values in farmland area, crop yields, and irrigation water requirements as compared to all FS scenarios (Fig. 5). Although the yield increase has a dampening effect on area demand for irrigated crop production, the results still show a steep increase of 245 km^2 additional irrigated farmland by 2025 and 592 km^2 by 2050. This area expansion is accompanied by an almost doubling of the irrigation water requirements by 2050 as compared to the baseline (618 MCM). The rainfed farmland area also shows a sharp increase from 1576 km^2 for the baseline to 2188 km^2 in 2025 and 3127 km^2 in 2050.

Table 2
Simulated areas for the focus land use/cover categories for the baseline (year 2000) and for the year 2025. Simulation results considering climate change are given as ensemble means (scenarios FS2, FS3, FSD2 and FSD3).

Scenario	Areas in km^2 (%) - 2025		
	Urban area	Irrigated farmland	Rainfed farmland
Baseline	1265	614	1576
FS1	1635 (29)	617 (0)	1554 (−1)
FS2	1265 (0)	700 (14)	1637 (4)
FS3	1635 (29)	701 (14)	1639 (4)
FD1	1265 (0)	859 (40)	2188 (39)
FSD1	1635 (29)	860 (40)	2194 (39)
FSD2	1265 (0)	966 (57)	2257 (43)
FSD3	1635 (29)	966 (57)	2270 (44)

3.4. Combined effects of changes in food supply and demand

Scenarios FSD1, FSD2, and FSD3 show how the combination of food supply factors (UE and CC) and food demand (SE) manifests itself in the landscape. Scenario FSD1 combines the effects of urban expansion and socioeconomic change. The simulation results for this scenario are almost identical to the results for the FD1 scenario, which is due to the dominant effect of increased crop demands on land use patterns and water requirements. The only difference between these two scenarios is in rainfed farmland, where we see slightly higher values for the FSD1 scenario. This can be attributed to slightly smaller crop yields (Fig. 5). A similar effect is visible for the comparison between the FSD2 and FSD3 scenarios, where differences are only visible for rainfed farmland area and yields. This is because the highly productive areas along the Jordan River and the KAC are used for cash crops that are typically irrigated. The (rainfed) production of staple food such as grains and cereals is pushed towards the more marginal lands where small changes in the location can have a detrimental effect on the already low rainfed crop yields. Overall, the latter two scenarios including CC and SE show the highest increase in farmland (1032–1045 ha by 2025 and 2618–2667 ha by 2050) and irrigation water requirements (162 MCM by 2025 and 437–439 MCM by 2050). For these, the dominating effect of additional food demand is combined with the detrimental effect of climate change on crop yields, and hence, farmland expansion. Given the scale of changes introduced by CC and SE, the effects of UE can be neglected.

4. Discussion

Urbanization is a significant development at the global scale (Seto et al., 2011; van Vliet et al., 2017) with important implications for

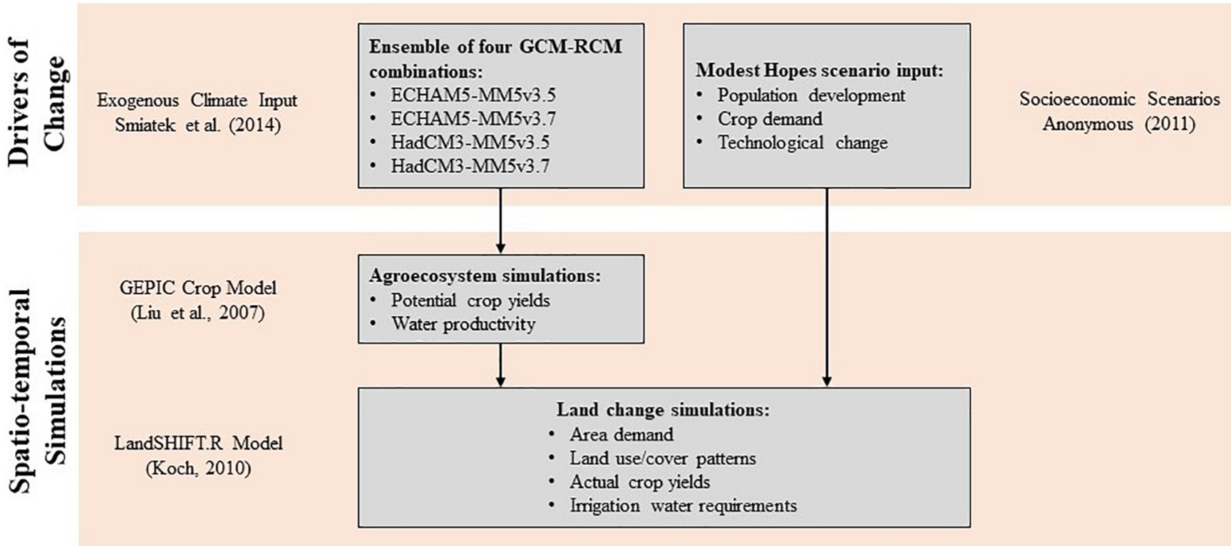

Fig. 2. Schematic view of the study's simulation workflow. We used climate input to GEPIC (Liu et al., 2007) simulations for potential crop yield and water productivity calculations. These were then used in combination with socioeconomic scenarios as input for land change simulations with LandSHIFT.R (Koch, 2010b).

food security and biodiversity (Güneralp et al., 2013). In our study, we analyzed the spatial effect of urbanization on land and water resources for The Hashemite Kingdom of Jordan. In contrast to typical scenario studies, we designed our study to be able to analyze and evaluate the isolated and combined effects of different components of the urbanization process. For this, we used a chain of simulation models to include multiple components of the land system and differentiated between the effects of food supply and food demand tied to urbanization and population growth. This is the first study to analyze the effects of urbanization on land change and irrigation water requirements in Jordan, making use of downscaled climate projections and spatially explicit, high-resolution land change simulations. In this section, we discuss our findings in the context of the two processes identified by Seto and Ramankutty (2016), analyze how the linkages between food supply and demand affect land and water resources and how they manifested themselves in the landscape at the regional scale.

4.1. Effects of changes in food supply and food demand

Cropland loss, driven by urbanization, has been a major concern in many parts of the world, such as China (Shi et al., 2016), Puerto Rico (López et al., 2001), or India (Pandey and Seto, 2015). Urban expansion often has a substantial effect on crop yields within a region, since fertile agricultural land is converted to urban areas and as a result, agricultural activities may be pushed to more marginal lands (Seto and Ramankutty, 2016). According to Seto and Ramankutty (Seto and Ramankutty, 2016), two characteristics describe in which countries cropland loss due to urban expansion are likely to occur: (1) countries that show a high urban population growth rate and a strong reliance on an agrarian economy, and (2) countries where fertile agricultural area is located in proximity to cities. With a current urbanization rate of 83% and expected increase of this rate to 89% in 2050 (United Nations, Department of Economic and Social Affairs (Population Division), 2015a), combined with the importance of agricultural activity for sustenance and income for a major part of the poor (Sidahmed et al., 2012), the Hashemite Kingdom of Jordan falls into the category of countries that are expected to experience farmland loss driven by urban expansion.

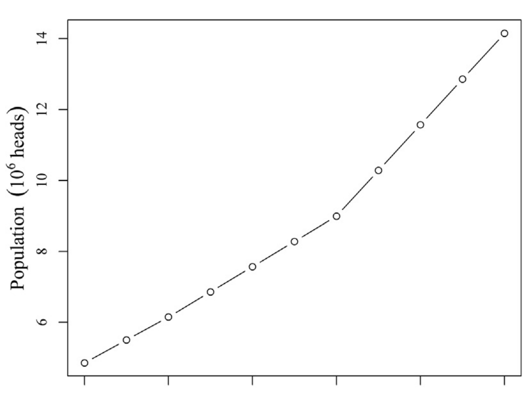

Fig. 3. Input information on population growth under the "Modest Hopes" scenario for the period 2000–2050 (Anonymous, 2011).

In the past, population growth in Jordan has resulted in land-use change and especially expansion of urban area (Al-Bakri et al., 2001; Potter et al., 2009). Saleh and Al Rawashdeh (2007) used Remote Sensing and GIS to analyze the expansion of Amman, Ma'daba, and Irbid and found an area increase from 106 km^2 to 163 km^2 for Amman, and from 4 km^2 to 11 km^2 for Ma'daba between the years 1983 and 2002. For Irbid, the authors found an increase in the urban area from 10 km^2 to 38 km^2 between the years 1983 and 2000. Compared to these observations, the simulation results for the FS1 scenario – analyzing the isolated effect of urban expansion – are in a realistic order of magnitude. Given that this study does not only focus on the major urban centers in Jordan, but on all urban areas, the projected increase in urban area from 1265 km^2 in 2000 to 1635 km^2 by 2025 and to 2099 km^2 by 2050 is feasible. Our simulations show 183 km^2 of urban area in areas formerly used as farmland by 2050. As a result, farmland is displaced to other areas in Jordan to fulfil the crop demands. Against expectations, the results of our study show that the displacement of farmland has no detrimental effect on crop yields or irrigation water requirements. On the contrary, the simulations indicate a slight increase in crop yields. This is because urban expansion pushes farmland into areas located in the Jordan Valley and the highlands along the King Abdullah Canal. These areas have high precipitation and high potential crop yields. Hence, we conclude that the isolated effect of urban expansion is not likely to impact food production in Jordan over the next few decades since sufficient fertile cropland is still available and irrigation infrastructure is in place to support irrigation agriculture. The downside of the dislocation of farmland to those areas is an average increase in the distance to markets of agricultural commodities.

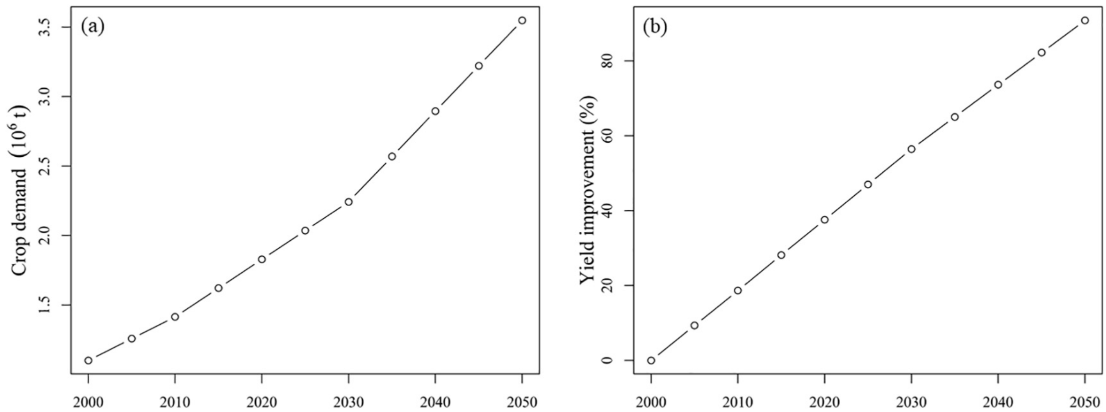

Fig. 4. "Modest Hopes" scenario assumptions on (a) crop demand, and (b) yield improvement due to advancements in plant breeding and agricultural management.

Unlike urban expansion, we found that another process influencing food supply – climate change – has a strong effect on the regional land and water resources. The study workflow includes downscaled climate data to calculate changes of potential crop yields and water productivity, which are used as the basis for calculating scenarios of land change and irrigation water requirements. This experimental design synthesizes different inputs and allows simulating the effect of climate change on food production with relatively high spatial detail. We only use one SRES scenario (Nakicenovic and Swart, 2000) as input for our analysis, but we considered four different downscaled climate data sets for the Jordan River region (Smiatek et al., 2011). The consideration of different climate realizations was important to understand the sensitivity of our modelling approach to climate data, to understand the range of uncertainty in our simulation outputs and to gain confidence in the results of our simulations (Sargent, 2013). The simulation results for FS2 – including only climate change - show a detrimental effect on crop yields and irrigation requirements, as well as the range of uncertainty introduced by different GCM-RCM combinations (Fig. 5). The latter increases over the simulation period. The decrease in crop yields due to less favorable climate conditions (higher temperatures and decreasing precipitation) leads to a significantly higher area demand for crop production and an increase in irrigation water requirements. These findings are in line with other studies on crop production and irrigation water requirements in the Mediterranean and the Middle East (Giannakopoulos et al., 2009; Koch et al., 2012b; Parry et al., 2004).

The analyses of urban expansion alone and in combination with climate change (FS1 - FS3) focuses on food supply. However, Seto and Ramankutty (2016) also argue for the consideration of food demand as an important aspect of urbanization. While we did not have appropriate data available to study the isolated effects of changes from rural to urban lifestyles on food demand, we did use scenario assumptions that include the effect of change in diets on food demand and that were specifically developed for the study area in the context of a multi-year scenario development process (Anonymous, 2011). Given the already high urbanization rate in Jordan, which projections show to increase in the future, we considered it important to analyze the effect of increasing food demand on land and water resources, and to compare it to the effects of changes in food supply. We consider the increasing food demand due to population growth, which in Jordan mainly takes place in urban areas (United Nations and Department of Economic and Social Affairs (Population Division), 2015a), in the scenarios focusing on socioeconomic change in Jordan. Besides the rising demand from population growth, the scenario assumptions also consider a change in dietary preferences as an important driver of demand change.

Our simulations results translate the changing demands for agricultural commodities into demands for area and irrigation water. The results indicate that – even though the scenario assumptions include an optimistic increase in crop yields (Fig. 4) – the increasing food demand leads to a significant expansion of cropland area (Tables 2, 3) and irrigation water requirements. Farmland areas, both irrigated and rainfed are likely to double, as are irrigation water requirements. The effect of a changing demand is multiple times higher than that of climate change alone (under the scenario assumptions specified above) (Fig. 5) and is likely to put additional pressures on food security in Jordan. With irrigation water requirements calculated to more than double by 2050, the results indicate additional detrimental effects on the already scarce freshwater resources (Hadadin and Tarawneh, 2007). In combination with changes in climate, the resulting increases of cropland demands and especially irrigation water requirements are even more pronounced, with the latter almost tripling (Fig. 5). In comparison to this, the effects of urban expansion are small.

4.2. Importance of regional studies and implications of findings

Global studies are of exceptional importance for the identification of broad trends, critical issues and concerns (Laurance et al., 2014; Myers et al., 2000; Seto et al., 2012), but they are not designed to work at a spatial resolution allowing the inclusion of processes and spatial heterogeneity required to provide details applicable to regional policy and decision-making. Dalla-Nora et al. (2014) and Lambin and Meyfroidt (2011) stress the necessity of connecting local and regional factors with global-scale factors to better understand the functioning of land systems. In this sense, an important objective of our study was filling the gap between coarse global studies and very detailed local studies.

Since urban expansion and its effect on the displacement of productive farmland is a concern at the global level, we were interested in its importance at the regional scale for Jordan. We designed our simulation study to compare and contrast three processes that contribute to global environmental change and operate on three different scale levels: urban expansion, climate change, and socioeconomic change. We used a scenario study as a method to specify meaningful combinations of global drivers such as climate change and regional factors such as assumptions regarding water infrastructure (e.g., Red Sea-Dead Sea Canal) and urbanization trends. With our modelling approach that couples a set of sub-models representing land-use processes (crop yields and land-use change) with high-resolution climate simulations, we were able to identify socioeconomic change in combination with climate change as dominant factors driving future land and water requirements. The simulation results depend on scenario assumptions and on the continuation of observed trends (e.g., population densities in urban areas and per capita area demands). Hence, the simulations are likely to differ from what will manifest itself in future landscapes as a result of stakeholder decision-making. However, scenario-based studies like the one presented here allow the exploration of regional trends and their quantification and visualization. We think that these results are valuable to

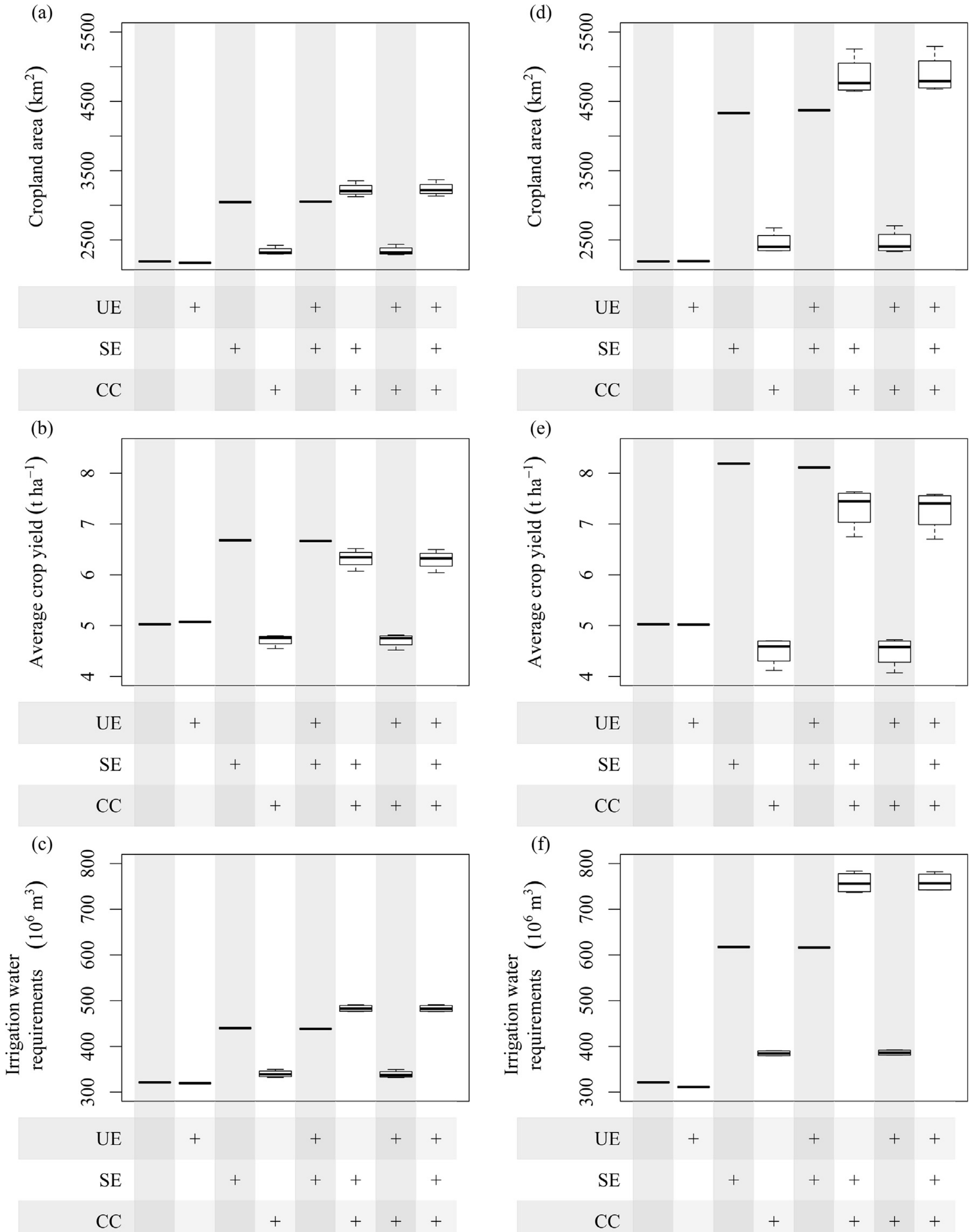

Fig. 5. Simulation results displaying (a) cropland area for the year 2025, (b) average crop yields for the year 2025, (c) irrigation water requirements for the year 2025, (d) cropland area for the year 2050, (e) average crop yields for the year 2050, and (f) irrigation water requirements for the year 2050.

inform regional decision makers and raise their awareness for different problem domains and their respective interlinkages.

The major outcome of this study is that, assuming continuation of current trends of population densities, farmland displacement due to urban expansion will not result in increasing farmland demands or decreasing regional crop yields. Urban expansion will also not lead to additional irrigation water requirements. In constrast, a change in climate is likely to add additional pressure to both land and water resources – as has been found in earlier studies (Koch et al., 2012a, 2012b). However, the effects of both of these components can almost be neglected when compared to the impact of additional food demand on land and water resources. This seconds the findings of Seto and Ramankutty (2016) and emphasizes the need for data allowing the analysis of outcomes due to changes in diet and lifestyle choices in general. Furthermore, while the effects of farmland displacement on land and water resources were minor, other important effects were not in the focus of this study. These include increases in impervious surface and changes in microclimate, which need to be considered in studies

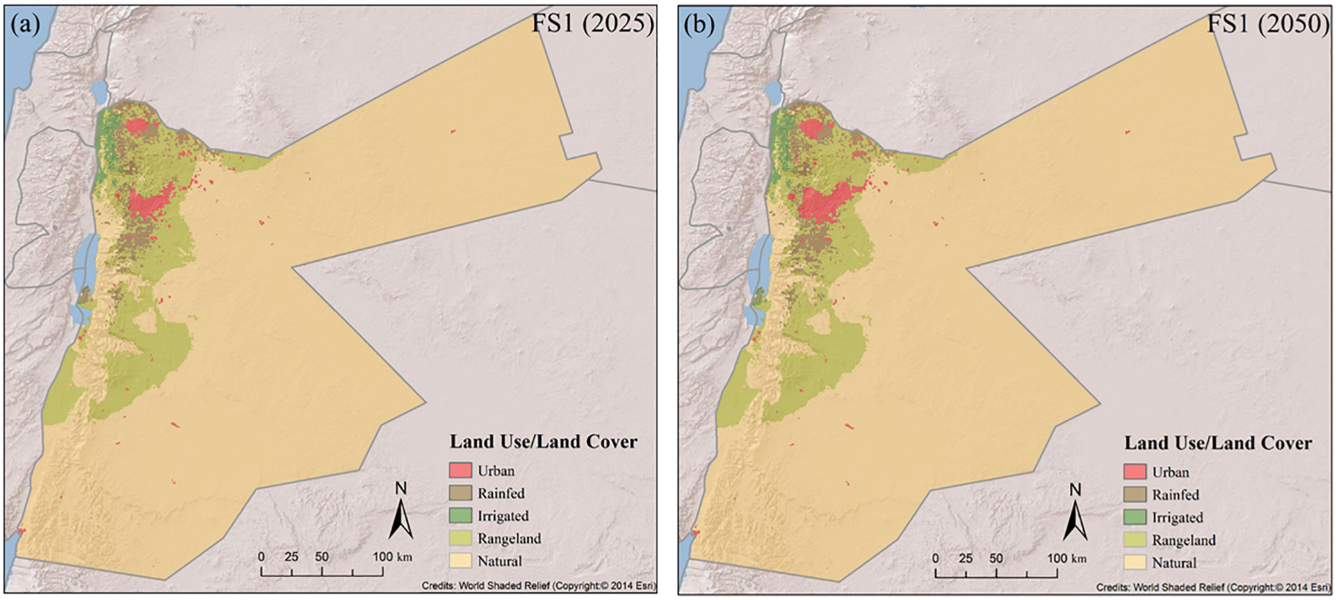

Fig. 6. Grid-based LandSHIFT.R simulation results for the FS1 scenario (a) for the year 2025 and (b) for the year 2050. LandSHIFT.R simulation output is calculated covering the entire Hashemite Kingdom of Jordan, with a spatial resolution of 30 arc sec.

similar to those conducted by Menzel et al. (2009), Smiatek et al. (2014), and Smiatek and Kunstmann (2016).

For Jordan, the findings of this study have important implications. With the recent approval of the Red Sea-Dead Sea Canal, an additional source of freshwater for irrigation will become available. While this may help to close the gap in water availability, the canal is also likely to introduce additional stress on the environment (Asmar and Ergenzinger, 2002). Furthermore, additional irrigation not only results in additional pressures on the environment, but also requires careful planning and trade-offs between different demands to be able to achieve them in a region of the world that is already experiencing high water scarcity (Hoff et al., 2011). Factors like new development of irrigation infrastructure are likely to require additional financial investments. Our simulation results include sufficient spatial detail and cover a broad range of assumptions about future development. The quantifications and visualizations of future land change provided by this study help improve the understanding of the magnitude of change. Early investments in additional infrastructure and adjustment in agricultural management may allow to change the trend of decreasing agricultural self-sufficiency in Jordan (Hadadin and Tarawneh, 2007).

5. Conclusions

The results of our simulation study do not serve as forecasts or predictions, but projections of likely future developments under scenario assumptions based on historical data and observations. Their value lies in providing estimates and improved understanding of future pressures on land and water resources, allowing for adjustments in planning and management. Combining our estimates of land demand and especially irrigation water requirements with spatially explicit simulations of future water availability will provide a more complete understanding of additional pressures on the hydrological system in a region already suffering from severe water stress. Also, improved understanding of gaps in water availability will allow for a better planning and development of infrastructure, since the adjustment of natural resource management will ultimately steer the manifestation of future use of land and water resources.

Table 3
Simulated areas for the focus land use/cover categories for the year 2050. Simulation results considering climate change are given as ensemble means (scenarios FS2, FS3, FSD2 and FSD3).

Scenario	Areas in km^2 (%) - 2050		
	Urban area	Irrigated farmland	Rainfed farmland
Baseline	1265	614	1576
FS1	2099 (66)	619 (1)	1576 (0)
FS2	1265 (0)	795 (29)	1660 (5)
FS3	2099 (66)	795 (29)	1668 (6)
FD1	1265 (0)	1206 (96)	3127 (98)
FSD1	2099 (66)	1205 (96)	3168 (101)
FSD2	1265 (0)	1576 (157)	3283 (108)
FSD3	2099 (66)	1577 (157)	3313 (110)

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